The quest for θ_{13} - A theoretical perspective -

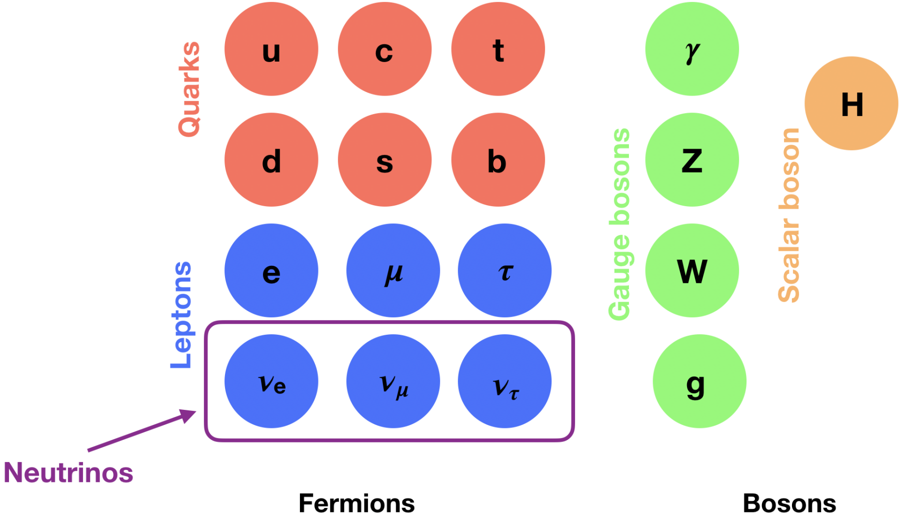
Julia Gehrlein

Brookhaven National Laboratory

BNL Daya Bay Colloquium

15th December 2020

Neutrinos in the SM



Role of neutrinos in the Universe

- second most abundant particle in the Universe:

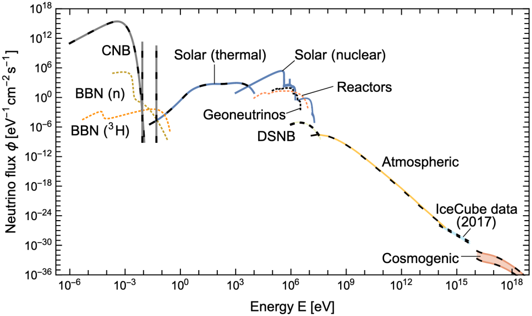
  a billion times more neutrinos than matter particles in the Universe

- 10^{38} neutrinos per second produced by the Sun

  (flux of $\sim$ 10^{11}/cm^2/sec at the Earth)

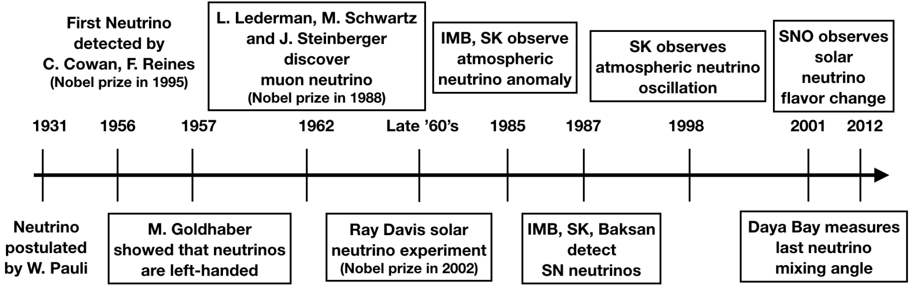
- 15 billion neutrinos from the Big Bang are in a large lecture hall

Role of neutrinos in the Universe [Vitagliano, Tamborra, Raffelt ’19]



- neutrino energies span 24 orders of magnitude
- different neutrino sources and production mechanisms
- lots of room for exciting neutrino physics & lots to learn!

Neutrino discoveries & BNL’s contribution



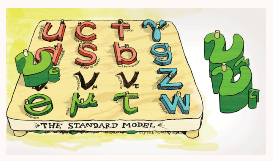
BNL had and has **big** impact on neutrino physics!

Neutrino oscillations

latest neutrino Nobel prize awarded to observation of flavor change of neutrinos:

only possible for massive neutrinos however neutrinos are massless in the SM

$\Rightarrow$ conclusive evidence for physics **beyond** the Standard Model!



Neutrino oscillations

flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS}: relates flavor and mass states

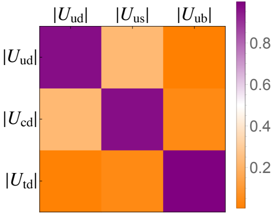
parametrized by 4 parameters (3 angles, 1 phase)

Quark mixing [PDG '20]

- Flavor mixing already present in the SM in the quark sector via the CKM matrix
- CKM matrix measured to a very good accuracy

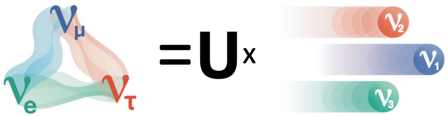
  $\rightarrow$ small mixing angles in the quark sector, CKM matrix is close to a diagonal matrix

$$\theta_{12}^{CKM} = 13.1^\circ,$$
$$\theta_{13}^{CKM} = 0.2^\circ,$$
$$\theta_{23}^{CKM} = 2.3^\circ$$



Shaped expectations for leptonic mixing matrix

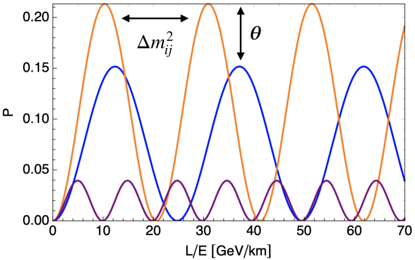
Neutrino oscillations



produce neutrino of flavor α with energy E

probability to detect neutrino with flavor β at distance L is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m^2_{ij} L/4E), \quad \Delta m^2_{ij} = m^2_i - m^2_j$$

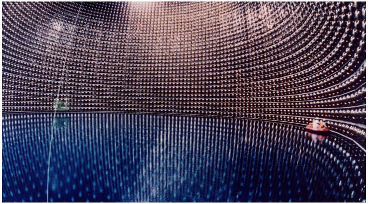


observation of neutrino oscillations introduced at least 6 new parameters to the Standard Model:

3 mixing angles, one CP violating phase, 2 mass splittings

$\Rightarrow$ **need** to measure them

Atmospheric mixing [hep-ex/9807003]



SuperKamiokande measured atmospheric mixing parameters:

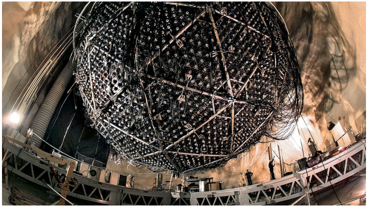
$$\theta_{23} \approx 45^\circ$$

$$\Delta m^2_{32} \approx 2.2 \cdot 10^{-3}\ \text{eV}^2$$

large flavor mixing between ν_2 and ν_3

surprising if compared to small quark mixing!

Solar mixing [nucl-ex/0309004]



SNO measured solar mixing parameters:

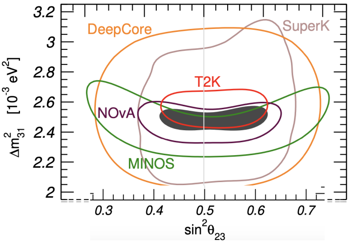
$$\theta_{12} \approx 30.2^\circ$$

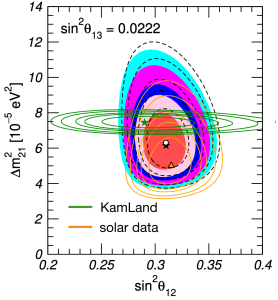
$$\Delta m^2_{21} \approx 5 \cdot 10^{-5}\ \mathrm{eV}^2$$

large mixing between $\nu_1,\ \nu_2$!

Solar and atmospheric mixing [nuFit v5.0]

SK & SNO measurements have been confirmed by other experiments like NOvA, MINOS, T2K, KamLand using man made neutrino sources like accelerator neutrinos or reactor neutrinos





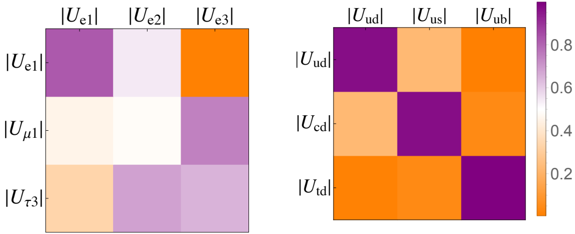
BNL contributed to these experiments (SK, SNO, MINOS)!

The last unknown mixing angle: θ_{13}

as of 2010:
last unknown mixing angle θ_{13}

earlier hints and theoretical prejudice that this mixing angle is **small**!

$\rightarrow$ lepton flavor models try to explain lepton mixing



Lepton flavor models

striking difference to quark mixing pattern: different origin of flavor

Quark mixing: small mixing angles, masses are hierarchical $\rightarrow$ continuous flavor symmetry

$$U_{CKM} \sim \mathbb{1} + \mathcal{O}(\lambda)$$

expansion parameter $\lambda \sim 0.22$ (Wolfenstein parametrization)

[Wolfenstein '83]

Lepton mixing: large mixing angles

$$U_{PMNS} \sim U_0 \not\sim \mathbb{1}$$

non-diagonal U_0 can be realized with discrete flavor symmetries

Lepton flavor models

discrete flavor symmetry as explanation for leptonic mixing
example: tri-bimaximal mixing

$$U_{PMNS} = U_{TBM} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & \mathbf{0} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ -1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

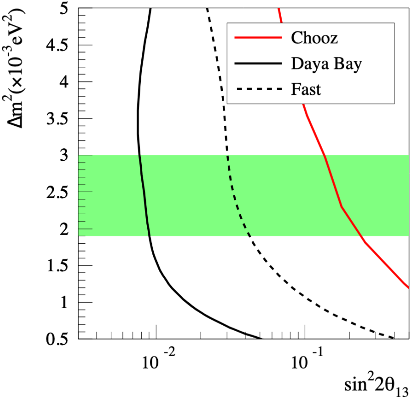
$$\theta_{23} = 45^\circ,\ \theta_{12} = \arcsin(1/\sqrt{3}) \approx 31.7^\circ,\ \theta_{13} = 0$$

many more models exist, they only differ by the predicted value of θ_{12}

$\Rightarrow$ theoretical expectation for θ_{13} shaped experimental program

The last unknown mixing angle: θ_{13}

sensitivity of Daya Bay [hep-ex/0701029]

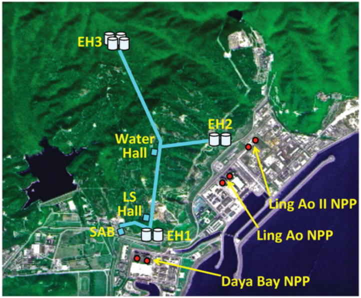


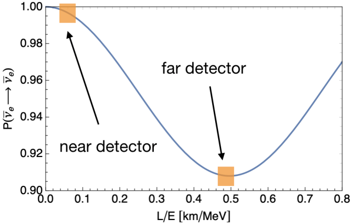
$\rightarrow$ Daya Bay had very good sensitivity to small angles

$\sin^2 2\theta_{13} \sim \mathcal{O}(0.01) \approx 3^\circ$

Daya Bay [1610.04802]

Daya Bay experiment measures **reactor anti electron neutrino survival probability**

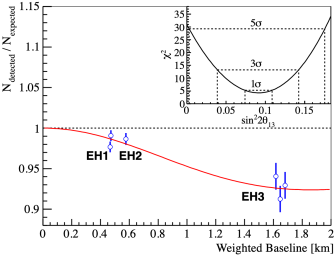




more details on the history of Daya Bay, BNL's involvement and the measurement will be covered in the following talks

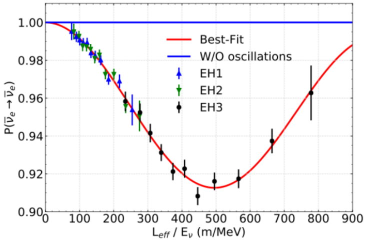
Daya Bay [1203.1669]

- 8 March 2012: Daya Bay publication using data from 24 December 2011-17 February 2012
- 6% deficit of electron neutrinos at far detector
  $\Rightarrow > 5\sigma$ evidence for non-zero θ_{13}

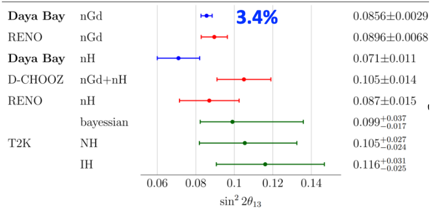


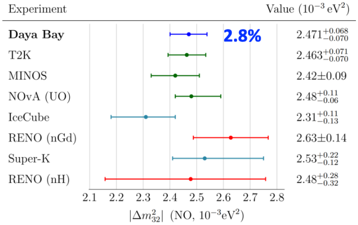
- publication in PRL has $>$ 2000 citations!

Daya Bay results [1809.02261, Ling @Neutrino2020]



Global comparison





Daya Bay has **world best** precision on θ_{13}

Implications of θ_{13} measurement

- completed determination of leptonic mixing angles: reduced unknown number of SM parameters

- confirmation of 3 flavor paradigm: agreement between atmospheric (ν_μ) and reactor (ν_e) mass splitting

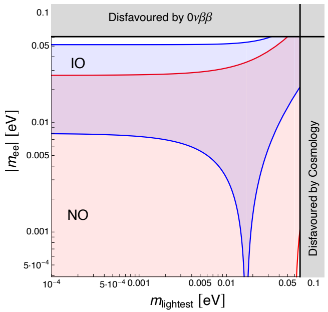
- determined fraction of ν_3 in electron neutrinos: reduce uncertainties in predicting neutrino related phenomena

Implications of θ_{13}: allowed parameter space for $|m_{ee}|$

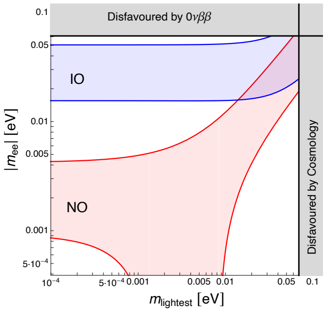
observable in neutrinoless double beta decay $\Rightarrow$ determines if neutrinos are Majorana or Dirac particles

$$|m_{ee}| = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right|$$

before Daya Bay measurement: θ_{13} unknown



after Daya Bay measurement: θ_{13} known

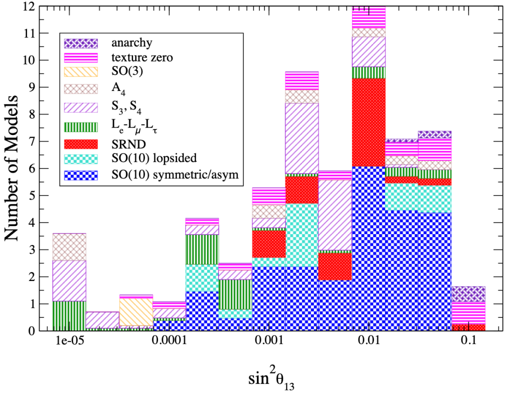


Implications of θ_{13} measurement

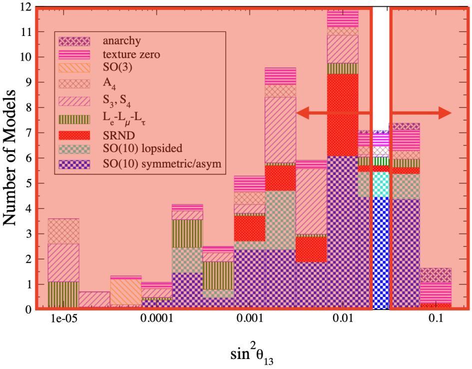
- completed determination of leptonic mixing angles: reduced unknown number of SM parameters
- confirmation of 3 flavor paradigm: agreement between atmospheric (ν_μ) and reactor (ν_e) mass splitting
- determined fraction of ν_3 in electron neutrinos: reduce uncertainties in predicting neutrino related phenomena
- guide flavor theory model building

Implications of θ_{13}: flavor theory [Albright, Chen '06]

predictions of models to explain observed mixing pattern



Implications of θ_{13}: flavor theory [Albright, Chen '06]



many flavor models ruled out $\rightarrow$ new ideas needed!

Implications of θ_{13} measurement

- completed determination of leptonic mixing angles: reduced unknown number of SM parameters
- confirmation of 3 flavor paradigm: agreement between atmospheric (ν_μ) and reactor (ν_e) mass splitting
- determined fraction of ν_3 in electron neutrinos: reduce uncertainties in predicting neutrino related phenomena
- guide flavor theory model building
- gateway to CP violation in lepton sector

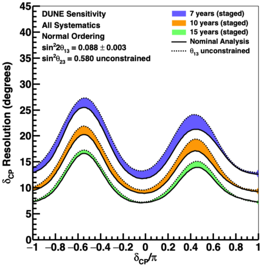
Implications of θ_{13}: gateway to CPV

only with 3 non-zero mixing angles CP violation possible

$$P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$
$$\propto \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos^2\theta_{13}\sin\delta$$

non-zero $\theta_{13} \Rightarrow$ possibility for CP violation in lepton sector!

next generation neutrino experiments like DUNE and T2HK will measure CPV and phase δ



[2002.02967]

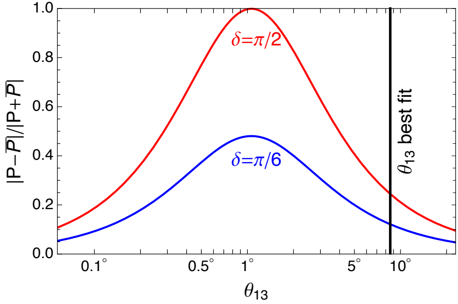
Implications of θ_{13} measurement

- completed determination of leptonic mixing angles: reduced unknown number of SM parameters
- confirmation of 3 flavor paradigm: agreement between atmospheric (ν_μ) and reactor (ν_e) mass splitting
- determined fraction of ν_3 in electron neutrinos: reduce uncertainties in predicting neutrino related phenomena
- guide flavor theory model building
- gateway to CP violation in lepton sector
- large θ_{13}: consequences for sensitivity of next generation of neutrino facilities to measure unknown neutrino parameters (δ and MO sensitivity)

Implications of θ_{13}: next generation neutrino experiments

Implications for the determination of unknown parameters

measurement of CP asymmetry for $P(\nu_\mu \to \nu_e)$

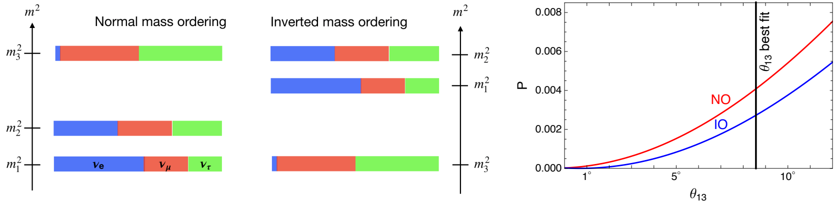


reasonable distinction power for different values of δ

Implications of θ_{13}: next generation neutrino experiments

Implications for the determination of unknown parameters

determination of mass ordering for $P(\nu_\mu \to \nu_e)$



distinction between NO and IO increases with θ_{13}

Future of neutrino physics

- many open questions in neutrino physics: CPV, MO, neutrino mass scale, nature & origin of neutrino masses, new neutrino interactions, additional neutrino species...
- BNL well positioned for the future of neutrino physics:
  - experimental contributions to DUNE, nEXO, PROSPECT, SBN, Rubin Observatory LSST
  - theory developments: oscillation theory, model building, theoretical calculations for neutrino processes, ...

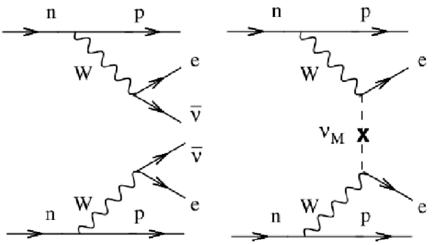
End of the talk

Thank you for your attention!

Backup: Neutrino observables

non-oscillation neutrino observables that depend on θ_{13}:
observable in neutrinoless double beta decay:

$$
\begin{aligned}
|m_{ee}| &= \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right| \\
&= \left| m_1 c_{12}^2 c_{13}^2 e^{-\phi_1} + m_2 s_{12}^2 c_{13}^2 e^{-\phi_2} + m_3 s_{13}^2 e^{-2\delta} \right|
\end{aligned}
$$



$\Rightarrow$ determine if neutrinos are Majorana or Dirac particles

Backup: Neutrino observables

non-oscillation neutrino observables that depend on θ_{13}:
kinematic neutrino mass:

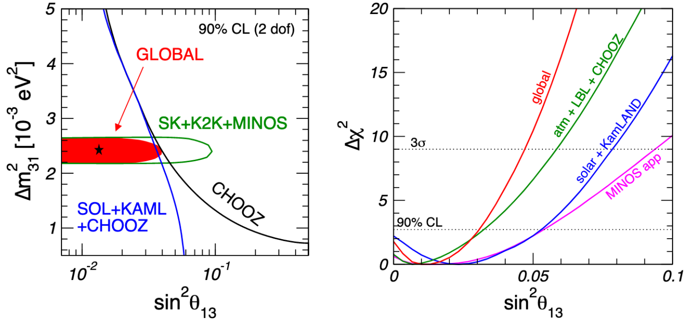
$$
\begin{aligned}
m_\beta^2 &= \sum_i |U_{ei}|^2 m_i^2 \\
&= m_1^2 \cos^2\theta_{12}\cos^2\theta_{13} + m_2^2 \sin^2\theta_{12}\cos^2\theta_{13} + m_3^2 \sin^2\theta_{13}
\end{aligned}
$$

$\Rightarrow$ information on absolute neutrino mass scale

current bound $m_\beta < 1.1$ eV [KATRIN experiment '20]

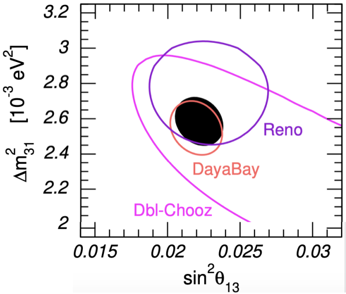
Backup: The last unknown mixing angle: θ_{13}

status May 2010 [1003.5800]



$\rightarrow$ only upper bounds on θ_{13} from atmospheric neutrino, reactor neutrino and long baseline experiments

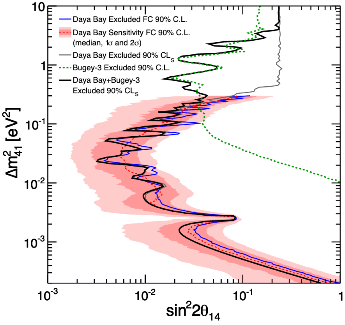
Backup: Daya Bay results [nuFit v5.0]



Daya Bay still has **world best** precision on θ_{13} & dominates global fits

Backup: Confirmation of 3 flavor paradigm

limits on sterile neutrinos



[2002.00301]

- search for an additional oscillation frequency besides Δm^2_{32} and Δm^2_{31}
- set the most stringent upper limit for light sterile neutrino signal with $\Delta m^2_{41} < 0.2$ eV^2

Backup: Implications of θ_{13}: flavor theory

many flavour models ruled out $\rightarrow$ new ideas needed!

way out: introduce corrections to predictions from discrete symmetries

$$U_{PMNS} \sim U_0 + \mathcal{O}(\epsilon)$$

interesting relation:

$$\theta_{13}^{PMNS} \approx \theta_{12}^{CKM} \sin \theta_{23}^{PMNS} \approx 9.3^\circ$$

(can be realized if charged lepton mixing matrix has CKM like structure since $U_{PMNS} = U_l^\dagger U_\nu$)

precision measurement of all PMNS parameters key to test and disentangle discrete flavor symmetries!